A Practical System for Measuring Film Thickness by Means of Laser Interference with Laminar-Like Laser

Feng ZHU,[1] Kazuhiko ISHIKAWA,[2] Toru IBE,[3] Katsuhiko ASADA,[1] and Masahiro UEDA[4]

[1]*Department of Information Science, Faculty of Engineering, University of Fukui, 3-9-1, Bunkyo, Fukui 910-0017*

[2]*Department of Electronics and Information Engineering, Fukui National College of Technology, Geshi, Sabae, Fukui 916-8507*

[3]*North Tec. Co. Ltd., 3-24-16, Ninomiya, Fukui 910-0015*

[4]*Department of Human Ecology and Technology, Faculty of Education and Regional Studies, University of Fukui, 3-9-1, Bunkyo, Fukui 910-0017*

A practical system for measuring a film thickness based on laser interferometry has been constructed using a laminar-like laser and a CCD camera. The system can measure a film thickness at a measuring frequency of 50 Hz, which enables real-time measurement in practical use. The measurable minimum thickness by means of a blue laser having a wavelength of 405 nm was 2.4 μm, and the maximum thickness was 1.2 mm for a film with a refractive index of 1.4. The measurement error of the film thickness due to the spherical aberration of the cylindrical lens was $\Delta h/h = 2\%$ at maximum, where h expresses film thickness and Δh its error amount.

Key Words: Measuring system, Film thickness, Interferometery, Laminar-like laser

1. Introduction

Thin films, for an example a lap film, and thin coatings, for examples an insulating vanish and a ceramic coating, have recently seen increasing use in many industries such as semiconductor and IC industries, the packaging industry, and the automobile industry. In these cases, accurate measurement of the thickness of coatings and films is very important for determining durability and cost performance. For direct measuring of the thickness of a thin film or a coating, we have proposed an optical method using laser interference at many incident angles.[1,2] However, this method could not measure the film thickness in real-time since the method required a movable mechanism to allow variations in the incident angle. We then improved the method so as to measure thickness in real-time by means of a sheet laser light and a CCD array sensor.[3-6] This method was based on a time smoothing of many reflected lights from slightly different irradiation positions. Thus, the method can measure thickness roughly in real time.

In this paper, a practical system for measuring film thickness essentially in real time has been devised which involves a laminar-like laser light and a CCD camera. The system's performance is also discussed.[7]

2. Principle and method

2.1 Previous method using a sheet laser light

The basic principle of this method depends on a multi-wave laser interference of both light reflected on the upper and lower surfaces of the coating, as was shown in the previous paper.[1] The reflective power of both surfaces affects only a contrast of the interfered light intensity and does not affect measurement errors of the thickness. An outline of the previous method using a sheet laser light is described in detail in this section. Figure 1 expresses the basic principle of this method. The basic optical arrangement consists of a laser, a collimator (not shown in this figure), two cylindrical lenses, and a photo-receiver. A sheet laser light is focused on the film as a point illuminator and is reflected onto a photo-receiver array. As is shown in this figure, each small portion of the sheet laser light is received on a corresponding small portion of the photo-receiver array such as ① to

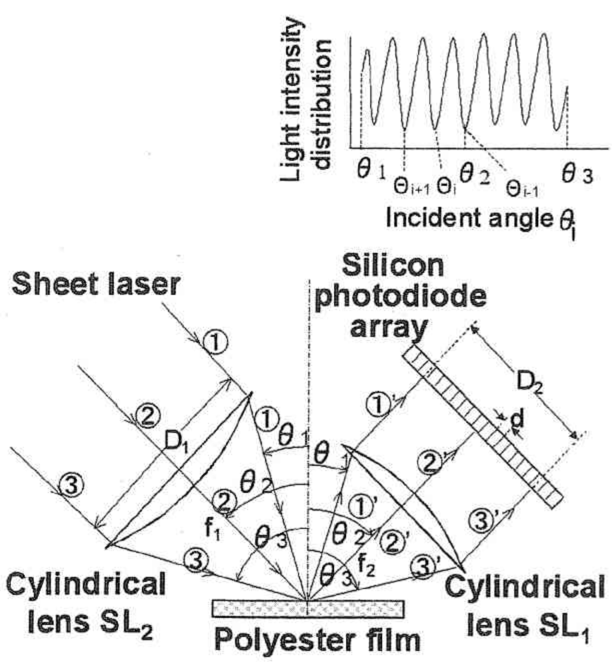

Fig. 1 Basic optical arrangement for measuring film thickness by means of laser interferometry.

①', and ② to ②'. This eliminates the need of a mechanism for varying the incident angles as required for the previous method.[1,2] The spatial resolution of incident angle, $\Delta\theta_m$, is then determined by an element size of the photo-receiver array, d, and a focal length of the cylindrical lens SL_2, f_2, as follows:

$$\Delta\theta_m d/f_2 . \tag{1}$$

The maximum variable range of the incident angle, $(\theta_3 - \theta_1)_{max}$ in this case, is given by which ever is the smaller of the two bellow:

$$(\theta_3 - \theta_1)_{max} = D_1/f_1, \quad \text{or} = D_2/f_2, \tag{2}$$

where θ_3 and θ_1 are the maximum and minimum incident angles, D_1 and D_2 the effective size of both cylindrical lenses SL_1 and SL_2, and f_1 and f_2 the focal length of these lenses.

The reflected lights on both the upper and lower surfaces of the film interfere with each other and result in a sign-like intensity distribution R on the CCD array sensor as is shown in a cut in Fig. 1, which is a basis of this method. The thickness of the film, h, can be expressed as follows:[1]

$$h = (\lambda/2)\left\{\left(n^2 - \sin^2\Theta_{i+1}\right)^{1/2} + \left(n^2 - \sin^2\Theta_i\right)^{1/2}\right\} \Big/ \left(\sin^2\Theta_i - \sin^2\Theta_{i+1}\right), \tag{3}$$

$$h = \left(\lambda/\sqrt{2}\right) \Big/ \left(2\sin^2\Theta_i - \sin^2\Theta_{i-1} - \sin^2\Theta_{i+1}\right)^{1/2}, \tag{4}$$

where Θ_i expresses the incident angle where the light intensity distribution has minimum values, n a refractive index of the film, and $\Theta_{i+1} < \Theta_i < \Theta_{i-1}$, as shown in a cut in Fig. 1. The above two equations are basically the same since each was derived from the same few equations.[8] Theoretically, equation (4) does not require a known n, but it requires three consecutive Θ, i.e., Θ_{i+1}, Θ_i, and Θ_{i-1}, and further rather high accuracy in Θ_i. On the contrary, Equation (3) requires only two consecutive Θ, i.e., Θ_{i+1}, Θ_i, but requires known n, and can be practically used for a known n.

2.2 Present method by means of laminar-like laser light

The above description was a basic principle of this method, which uses a sheet laser light. The largest problem involved in this method was a large fluctuation in the light intensity distribution on the photo-receiver array, which makes an accurate determination of Θ_i difficult.[4] However, this problem can be solved by means of the smoothing of many data. Two methods are considered for this smoothing: one is time smoothing, and another is spatial smoothing. Time smoothing was achieved in the previous method by means of a sheet laser light,[4] which requires a slight shift of the film. This prevents this method from measuring the thickness of a layer essentially in real time. The method was further improved so as to measure the film thickness essentially in real time by means of a laminar-like laser light. Figure 2 expresses the optics for this method, which uses spatial smoothing. The laminar-like laser light with a width W is focused onto a line on the film, and is reflected onto the cylindrical lens SL_2, which is received on the CCD camera with horizontal dimension D_2 and vertical dimension W. In the previous method, an irradiated position O on the film was slightly moved by shifting the film, and many light intensity distributions from these irradiated points were smoothed in time, i.e., time smoothing. On the contrary, many light intensity distributions arisen from line O'OO" are recorded on a 2-D CCD camera by only one flash of laser light, and smoothed in space, i.e., spatial

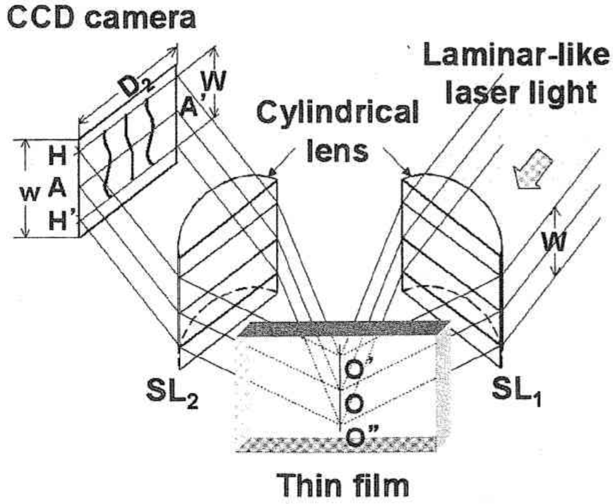

Fig. 2 Basic optics for measuring film thickness by means of laminar-like laser light.

smoothing. This enables essentially real-time measurement, because the method does not require shifting of the film.

2.3 Determination of Θ_i

The method in this study requires only two or three successive incident angles Θ_i for a determination of film thickness, as was shown in equations (3) and (4). This is one of the main advantages over other similar methods, the method of beam profile reflectometry for example.[9]

Figure 3 shows an example of the interference pattern on the CCD camera, i,e., the light intensity distribution, to obtain spatial smoothing.[7] The light intensity distribution on each horizontal line is arisen from each corresponding position on a line O'OO" on the film, and all the data on a line O'OO" are recorded on the CCD camera. Each light intensity distribution can, basically, be used for the determination of Θ_i.

However, the angle Θ_i cannot be determined from this distribution, because it fluctuates considerably due to speckles inherent in laser light as is shown in Fig. 4(a). Such fluctuation can, however, be decreased by smoothing many sampling data on the horizontal lines. The method of spatial smoothing is basically the same as that of time smoothing. Figure 4 shows this smoothing effect in space. Thus, the smoothing by N samples decreases the fluctuation remarkably; the fluctuation is linearly proportional to $1/\sqrt{N}$, when the sampling data have usually a normal distribution.[10,11] The angle Θ_i can then be determined

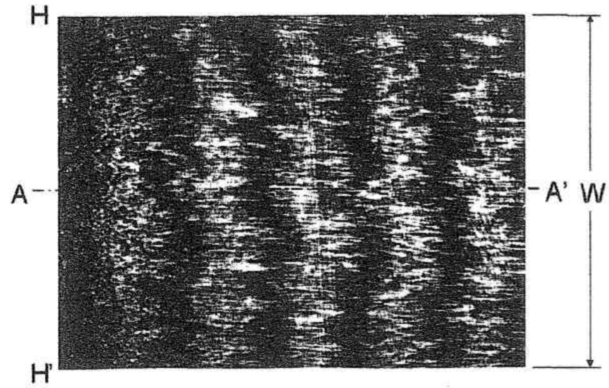

Fig. 3 Interference pattern on the CCD camera for spatial smoothing.

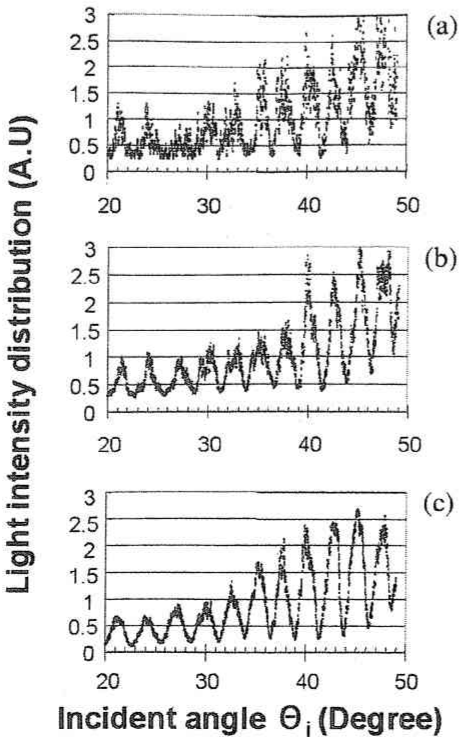

Fig. 4 Smoothing effect by means of the light intensity distribution on each horizontal line: (a) no smoothing, (b) smoothing by 10 samples, (c) smoothing by 50 samples.

accurately based on this smoothed intensity distribution, as follows.

Figure 5 expresses an example of a light intensity distribution in an enlarged incident angle scale and an approximate line by means of the method of least squares at extremely limited range of the incident angle. An inclination of this straight line should be zero at the minimum and maximum of this intensity distribution. Such lines within each extremely limited range were calculated over the whole range of incident angles. The angle Θ_i can then be obtained from these lines.

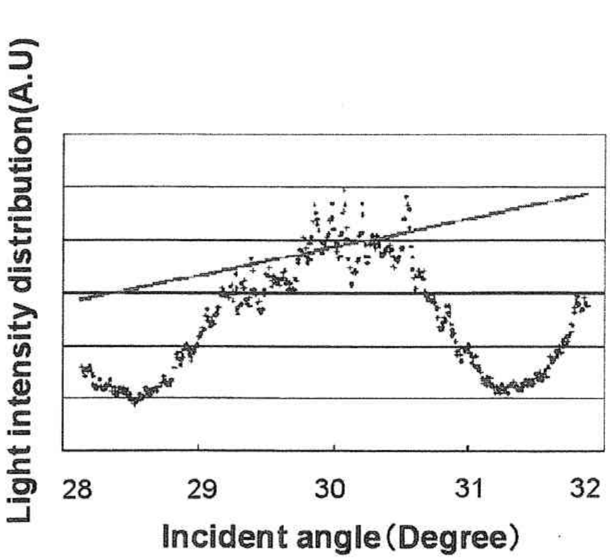

Fig. 5 Approximate straight line determined by means of the method of least squares.

3. Performance of the practical system

A practical system was constructed. Figure 6 shows the appearance of this system, and Table 1 its main performance.

The measurement frequency of a film thickness was determined mainly by the sample number for smoothing, N, and the speed of a 16 bit A/D converter in the processing circuit. The frequency was about 50 Hz, which is almost enough for practical use.

The measurable minimum thickness of the film is 2.4 μm, and the maximum thickness is about 1.2 mm for the laser with a wavelength of 405 nm and the refractive index of a film of 1.4, which is discussed in section 4.1.

The working distance between the sample and the system head is about 7 mm.

A variable range of incident angle, $\theta_1 \sim \theta_3$ in Fig. 1, was limited to a rather small range of ± 12 ° from the optical axis inclined 45 ° in the horizontal direction from the consideration of measurement error due to the spherical aberration of both cylindrical lenses. This lowers the resolution of this optical system, in other words, increases the smallest measurable film thickness to about three times of the value obtained by the variable range of 0 ° ~ 90 °.[1-3] However, this small range of incident angle reduces the measurement error of the film thickness, as is discussed in 4.2.

4. Discussion

4.1 Measurable minimum thickness and maximum thickness

Film thickness can be calculated by means of equations (3) or (4). Thus, two or three consecutive Θ_i should exist between 45 ° ± 12 ° for this calculation. The pitch of the light intensity distribution, i.e., an angle between each Θ_i, increases when the

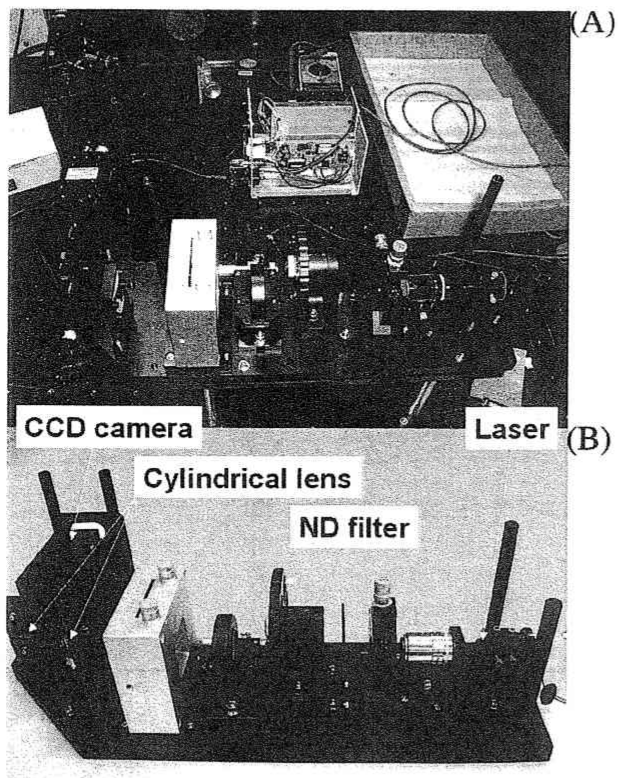

Fig. 6 Appearance of the system. (A) Top view, and (B) side view.

Table 1 System performance.

Measuring frequency	50 Hz (in Standard)
Measurable minimum thickness	2.4 μm (for Refractive index of 1.4)
Measurable maximum thickness	1.2 mm (for Refractive index of 1.4)
Working distance	7 mm
Adaptability	Film, Coating
Variable angle of the incident light	33°~57°
Wave length of the laser	405 nm
CCD size	5 mm (Height) ×8.8 m (Length), Resolution 10 μm
Focal length of the cylindrical lens	f_1=50mm, f_2=25mm

thickness diminishes, and two consecutive Θ_i can't exist in this range of incident angle when the thickness becomes too small, as is shown in Fig. 7. This determines the measurable minimum thickness h_{min}, in other words, the spatial resolution of this method, as follows;[1)]

$$h_{min} \geq \lambda \Big/ \left\{ \left(n^2 - \sin^2\theta_{1p}\right)^{1/2} - \left(n^2 - \sin^2\theta_{3p}\right)^{1/2} \right\}, \tag{5}$$

where θ_{1p} is the practical minimum incident angle, and θ_{3p} the maximum incident angle, which are 33 °(= 45 ° - 12 °) and 57 ° (= 45 ° + 12 °) for this practical system, respectively, as described above. Thus, the spatial resolution can be determined by the wavelength of the laser, the refractive index of the film, and the minimum and maximum incident angles. As an example, $h_{min} \approx 5.9\ \lambda = 2.4$ μm can be obtained for $\lambda = 405$ nm and n = 1.4.

On the other hand, the measurable maximum thickness is determined by the spatial resolution of an incident angle δ_θ, defined by

$$\delta_\theta = d / f_2, \tag{6}$$

where d is the spatial resolution of the CCD camera in the horizontal direction, and f_2 the focal length of the cylindrical lens SL_2. In this system, the angle resolution was found to be $\delta_\theta = 4.0 \times 10^{-4}$ for d = 10 μm and f_2 = 25 mm. Theoretically, one pitch of the light intensity distribution can be reproduced only by two sampling data as based on the sampling theory.[11)] Thus, it is practically sufficient to use ten sampling data for that reproduction. That is, the maximum measurable thickness h_{max} can

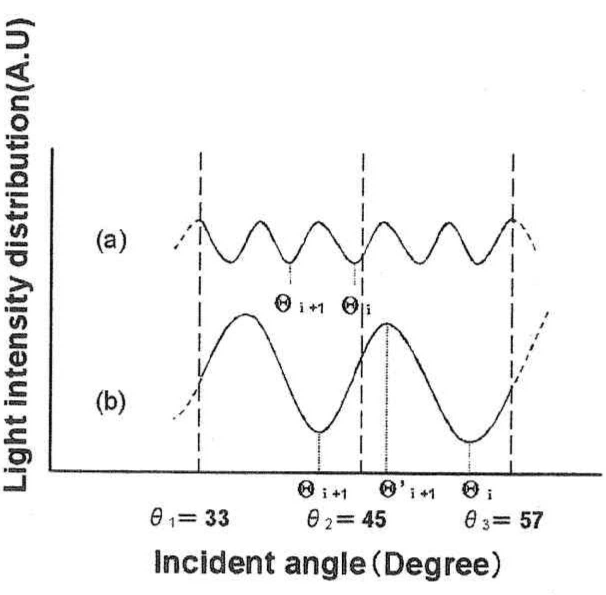

Fig. 7 Light intensity distribution for thick (a) and thin (b) films.

be obtained when two consecutive minimum of the light intensity distribution exist within $10\delta_\theta = 4.0 \times 10^{-3} = 0.023$ °. For example, h_{max} becomes 3020 $\lambda \approx 1.22$ mm by substituting Θ_i = 45.0 ° and Θ_i = 45.023 ° into equation (3) for λ = 405 nm and n = 1.4.

4.2 Error due to a spherical aberration of the cylindrical lens

The measurement error of the film thickness is caused by a measurement error of Θ_i, since the film thickness can be calculated by means of this value as shown in equation (3) or (4). One main factor for this error is caused by a spherical aberration, which is attendant on the usual lens. This becomes nearly zero at the center of the lens, i.e., the optical axis of the lens, and increases at the edge. Thus, the angle Θ_i has little error near the optical axis, but has large error far from the optical axis. As was shown in Fig. 7, the thickness of thick film can then be calculated correctly by means of two successive Θ_i near the optical axis, since there are many values of Θ_i in this range of incident angle. However, the thickness of thin film may have a large error, since either of the two Θ_i has a large error, $\Delta\theta$. A considerable maximum error occurs when Θ_{i+1} exists near the optical axis, and Θ_i near the end, as shown in Fig. 7 (b). In this case, the maximum error in h, Δh_m, can be calculated by substituting $\Theta_i \rightarrow \Theta_i + \Delta\theta$ into equation (3) as follows:

$$\Delta h_m / h \approx \Delta\theta \sin\Theta_i \cos\Theta_i \left[\left(n^2 - \sin^2\Theta_i\right)^{-1/2} \Big/ \left\{ \left(n^2 - \sin^2\Theta_i\right)^{1/2} + \left(n^2 - \sin^2\Theta_{i+1}\right)^{1/2} \right\} + 2 \Big/ \left(\sin^2\Theta_i - \sin^2\Theta_{i+1}\right) \right]. \tag{7}$$

The position error of the light ray on a CCD camera due to the spherical aberration, Δ_s, was about 100 μm for the light ray directed at the ends θ_s, 12 ° in this system. The angular error due to this position error, $\Delta\theta_s$, was then calculated as follows:

$$\Delta\theta_s = \Delta_s \cos\theta_s / f_2, \quad \text{or}$$
$$\Delta\theta_s{}^\circ = \left(\Delta_s \cos\theta_s / f_2\right)\left(180^\circ/\pi\right). \tag{8}$$

Substituting θ_s = 12 °, Δ_s = 100 μm, and f_2 = 25 mm into equation (8), we obtain $\Delta\theta_s = 3.9 \times 10^{-3}$ or $\Delta\theta_s{}^\circ = 0.22$ °. A considerable maximum error occurs in the case of Θ_{i+1} = 45 ° and Θ_i = 57 °. This yields maximum error in h;

$$\Delta h_m / h = -5.1 \times \Delta\theta_s = -0.02 \ (\text{for } n = 1.4). \tag{9}$$

The considerable maximum error rate in h, $\Delta h/h$, was within 2 %, even when the film thickness is as small as a few light wave lengths.

4.3 Error due to an estimation of Θ_i

The light intensity distribution was roughly a sine wave as was shown in Fig. 4. One of the two consecutive values of Θ_{i+1} and Θ_i, in this case Θ_i, can then be estimated by means of the incident angle Θ_{i+1}', where the light intensity distribution has a maximum value, as shown in Fig. 7 (b). The estimated value of Θ_i, Θ_i', can therefore be expressed as follows,

$$\Theta_i' = \Theta_{i+1} + 2\left(\Theta_{i+1}' - \Theta_{i+1}\right). \tag{10}$$

Thus, the measurable minimum thickness can further be half of the value expressed by equation (5) by means of this estimated value of Θ_i'. However, this yields an error in Θ_i, and then in h as follows.

Table 2 Error between estimated angle Θ_i' and measured angle Θ_i.

Θ_{i+1}°	Θ'_{i+1}°	Θ'_i°	$\|\Theta'_i° - \Theta_i°\|$
19.9569	21.2118	22.4667	0.1725
22.6392	24.0510	25.4628	0.0705
25.5333	27.1176	28.7019	0.2039
28.4980	30.0745	31.6510	0.3373
31.3137	32.5765	33.8393	0.0548
33.8941	35.2745	36.6549	0.1725
36.4824	37.5804	38.6784	0.2118
38.8902	39.9569	41.0236	0.3293
41.3529	42.7725	44.1921	0.4078
43.7843	45.1098	46.4353	0.1177
46.3176	47.7137	49.1098	0.5020
48.6078	—	—	—

Table 2 expresses the error between estimated angle Θ_i' and the measured angle Θ_i for the previous data.[4,5] The maximum error in Θ_i was about 0.5 °, which yields an error in h, $\Delta h/h \approx 0.06$ from equation (9), as an example.

5. Conclusion

A practical system for measuring film thickness has been constructed and its performance has been discussed. The system consists of two main sub-systems; one is an optical system composed of a laser having a wavelength of 405 nm, two cylindrical lenses, and a CCD camera, and another is a data processing system. The main performance of this system is as follows, for a variable angle of incident light of 33 ° ~ 57 °, a laser wavelength of 405 nm, and a film refractive index of 1.4.

(1) The measuring frequency is about 50 Hz in standard use.

(2) The measurable minimum thickness is 2.4 μm, and the maximum thickness is 1.2 mm.

(3) The working distance is 7 mm, which is sufficient for practical use.

Acknowledgements

We want to express our appreciation to H. Sangu and R. Okoshi of the Siguma Koki Co. Ltd. for their technical support in developing this practical system.

References

1) K. Ishikawa, H. Yamano, K. Kagawa, K. Asada, k. Iwata, and M. Ueda: Opt. Lasers Engr. **41** (2004) 19.
2) M. Ueda and K. Ishikawa: Pat. Pending No. 2002-86938.
3) K. Ishikawa, F. Murase, Z. Feng, and M. Ueda: Rep. 308th Topical Meeting, Laser Soc. Jpn. Laser Measurements, No. RTM-03-09(2003) pp. 23.
4) K. Ishikawa, H. Yamano, K. Asada, k. Iwata, and M. Ueda: Opt. Lasers Engr. **41** (2004) 731.
5) M. Ueda and K. Ishikawa: Pat. Pending No. 2002-206290.
6) M. Ueda, K. Ishikawa, and Iwata: Pat. Pending No. 2003-067254.
7) F. Zhu, K. Ishikawa, T. Ibe, and M. Ueda: Rep. 320th Topical Meeting, Laser Soc. Jpn. No. RTM-04-01(2004) 1.
8) T. Tsuruta: Applied Optics I and II: (1998) 33 (in I) and 114 (in II).
9) N. Iwasa: Electronic Materials **6** (1998) 1.
10) M. Ueda, K. Ishikawa, C. Jie, S. Mizuno, and M. Tsukamoto: Rev. Laser Engng. **21** (1993) 42.
11) B. P. Lathi: *Communication system*, New York: Wiley (1968) p. 130.